

# Synchronizing focus error detection of dual-pickup heads in a multi-layer data storage system

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**Abstract** To implement a dual-pickup-head multi-layer data storage system, it is necessary to measure the synchronizing focus error of the two pickup heads to validate the feasibility of the focus servo method. By using the ABCD transforming matrix method of geometric optics, we calculate the relationship between the output energy and the space interval of the two heads. After confirming the detection system working in the linear area, the voice coil motors of the two pickup heads were driven by sine signals with different frequencies and recorded the output signals of the quadrant photo-detector under different movement states respectively, including static, lower pickup head movement and dual-pickup-head synchronizing movement. The synchronizing focus error, which is caused by the characteristic parameter mismatch of the two pickup heads, could be obtained through frequency-domain analysis of these output signals. The experimental result shows that the amplitude of synchronizing focus error under 20 Hz is less than 1  $\mu\text{m}$ , which could adequately satisfy the focus servo requirement of the multi-layer data storage system.

**Keywords** three-dimensional optical data storage, error detection, optical pickup head, coil motor, focus servo

## 1 Introduction

As the carrier of information, data storage technology is becoming more and more important. The widely used two-dimensional storage technology cannot satisfy the needs of society any more because of diffraction and storage capacity limits. In 1989, Rentzepis pointed out that by using the two-photo nonlinear absorption effect of some inorganic or organic material, we could realize three-dimensional high-capacity data storage, and the storage

capacity could reach  $10^6 \text{ MB/cm}^3$  [1]. To make this technology progress towards practical use, we put forward and constructed a confocal dual-pickup-head multi-layer data storage system based on CD/DVD servo technology [2]. The writing laser is pulsed laser, featuring wavelength of 800 nm, repeat frequency of 80 MHz, and pulse width of 80 fs. By driving the upper pickup head with the focus servo control signal of the lower pickup head, we realized the synchronizing movement of the two pickup heads and focused the upper head position in a specific layer of storage material. Meanwhile, by using the linear displacement characteristics of the voice coil motor, we realized layer selection and three-dimensional reading and writing by applying different DC voltages on the focus actuator of the upper voice coil motor [3]. The astigmatism caused by the continuously approaching focus beam toward the disk will lead to a bigger information bit and weaker signal intensity as the storage depth increases. This problem could be solved by using the method of astigmatism compensation of the Kepler system [4]. In addition, although the model number and nominal transfer function of upper and lower pickup heads are the same, a fine distinction exists from one pickup head to another in the actual manufacturing process and in their transfer functions. Under the same driving signal, the upper and lower pickup heads cannot move in complete synchronization. Hence, the focus beam cannot be positioned in a specific layer in the storage material and information could not be written and read effectively. Before carrying out the data storage experiment of a confocal dual-pickup-head multi-layer data storage system, we must also detect the synchronizing focus error of the two heads and ensure whether it could satisfy the needs of focus servo and position precision.

## 2 Principle of error detection

Figure 1 is the schematic diagram of the confocal dual-pickup-head multi-layer data storage system we

Translated from *Acta Optica Sinica*, 2007, 27(4): 685–689 [译自: 光学学报]

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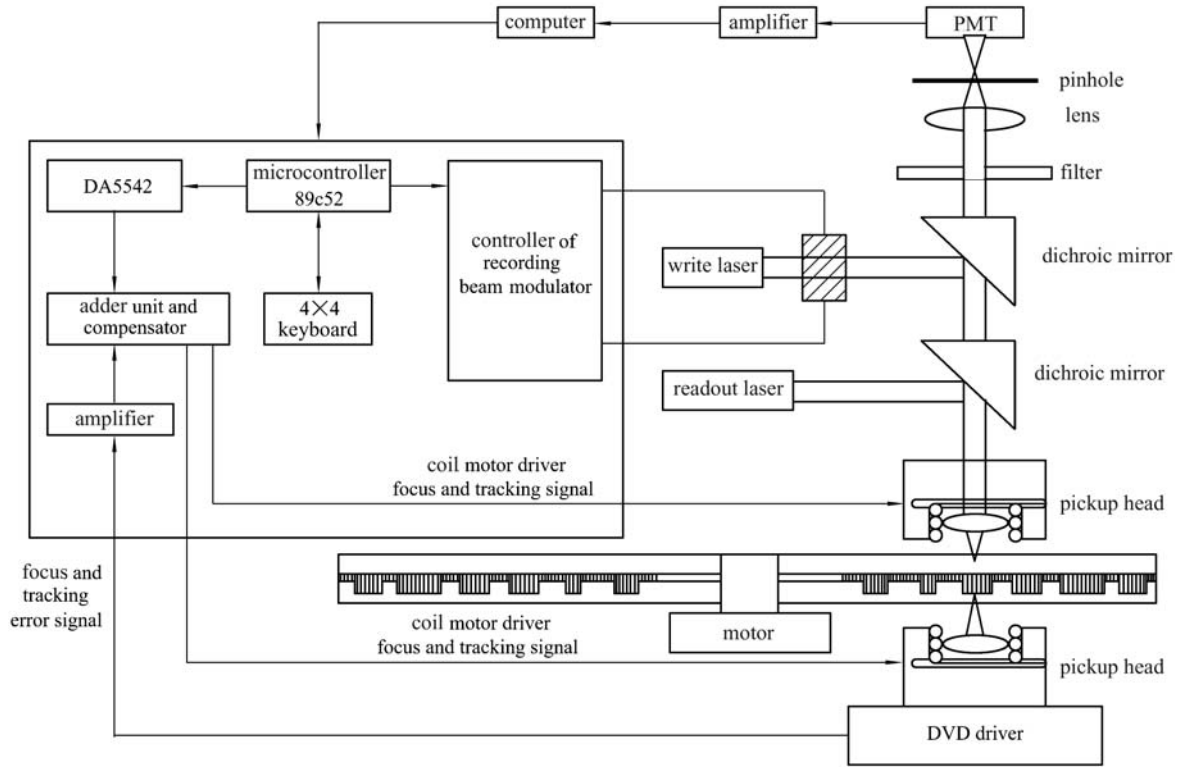


Fig. 1 Schematic diagram of confocal dual-pickup-head multi-layer data storage system

constructed. Figure 2 is the schematic diagram of a dual-pickup-head synchronizing error detection system.  $L_1$  and  $L_2$  are object lens of the upper and lower pickup heads respectively. The limiting aperture is  $2a$ , focal length is  $f_1$ , and the space length is  $d$ .  $L_3$  is a biconvex lens with limiting aperture of  $2b$  and focal length of  $f_2$ . The space length between  $L_2$  and  $L_3$  is  $x$ , while the space length between  $L_3$  and the surface of quadrant photodetector is  $c$ .  $e$  is the side length of the quadrant photodetector's effective induction zone.

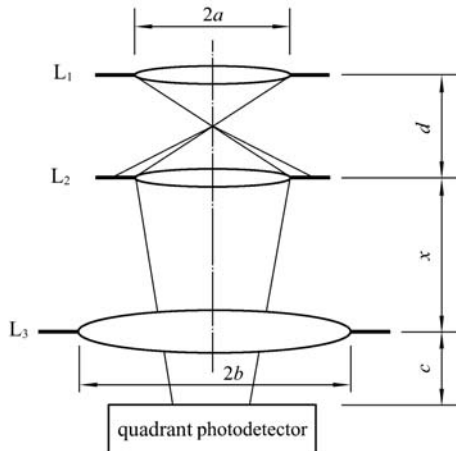


Fig. 2 Schematic diagram of synchronizing focus error detection system

According to the ABCD transforming matrix calculation method [5], the input ray and transforming matrixes are listed as follows:

1) Input ray:

$$U_i = \begin{pmatrix} a \\ 0 \end{pmatrix}. \quad (1)$$

2) Transforming matrixes of all lenses:

$$L_1 = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix}, L_2 = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix}, L_3 = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{pmatrix}. \quad (2)$$

3) Transfer transforming matrixes of free space:

$$M_1 = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}, M_2 = \begin{pmatrix} 1 & x \\ 0 & 1 \end{pmatrix}, M_3 = \begin{pmatrix} 1 & c \\ 0 & 1 \end{pmatrix}. \quad (3)$$

The coordinates of input rays on the input surface of all optical devices can be calculated as follows:

$$U_{1i} = U_i, U_{2i} = M_1 L_1 U_{1i}, U_{3i} = M_2 L_2 U_{2i}, U_{4i} = M_3 L_3 U_{3i}. \quad (4)$$

To make the output signal of the quadrant photodetector change with the space length  $d$  between  $L_1$  and  $L_2$ , and only relate with  $d$ , the coordinates of input rays on the input surface of all optical devices must satisfy

$$\begin{cases} |U_{2i}(1,1)| > a, \\ |U_{3i}(1,1)| < b, \\ |U_{4i}(1,1)| < e \end{cases} \Rightarrow \begin{cases} \left| a \left( 1 - \frac{d}{f_1} \right) \right| > a, \\ \left| a \left( 1 - \frac{x}{f_1} \right) \left( 1 - \frac{d}{f_1} \right) - a \frac{x}{f_1} \right| < b, \\ \left| \left( 1 - \frac{c}{f_2} \right) \left( a \left( 1 - \frac{x}{f_1} \right) \left( 1 - \frac{d}{f_1} \right) - a \frac{x}{f_1} \right) - a \frac{c d}{f_1 f_2} \right| < e. \end{cases} \quad (5)$$

Under this condition, the output energy of  $L_2$  could be calculated according to:

$$\begin{cases} I(r,z) = \frac{I_0 \omega_0^2}{\omega^2(z)} \exp\left(-\frac{2r^2}{\omega^2(z)}\right), \\ Y(z) = \int_0^a \int_0^{2\pi} r I(r,z) dr d\theta \\ = \frac{\pi I_0 \omega_0^2}{2} \left[ 1 - \exp\left(-\frac{2a^2}{\omega^2(z)}\right) \right]. \end{cases} \quad (6)$$

In  $z = d - f_1$ , which stands for the space length from  $L_2$  to the waist of the input Gauss beam,  $I_0$  is central light intensity of the waist of input Gauss beam,  $\omega_0$  is radius of the waist,  $\omega(z)$  is width of the Gauss beam. The relationship between  $Y(z)$  and  $z$  is shown in Fig. 3. According to the figure, a linear area exists in the curve, where the distance variation of the two pickup heads could be linearly transferred into the variant output electric signal of the quadrant photodetector. Because the Gauss beam is collimated and the offset of the object lens is no more than 1.5 mm, the beam could be regarded as parallel light. The movement of the upper pickup head's object lens will not lead to the apparent change of the input beam, i.e., it could be approximately taken as upper

pickup head static and slight lower pickup head movement when the two heads move in synchronicity.

Let  $G(s)$  be the nominal transfer function of the focus actuator of upper and lower pickup heads and the actual transfer function is  $G_1(s)$ ,  $G_2(s)$  respectively. The input driving signal is  $U(t) = A_0 \sin(2\pi f t)$ .  $Y_0(t)$ ,  $Y_s(t)$  and  $Y_d(t)$  are the output signals of the quadrant photodetector under initial static state, lower pickup head movement state, and dual-pickup-head synchronizing movement state, respectively.  $X_1(t)$  and  $X_2(t)$  are the displacements of upper and lower pickup heads respectively, while  $\Delta(t)$  is the synchronizing focus error. Corresponding frequency domain signals of these time domain signals are  $U(s)$ ,  $Y_0(s)$ ,  $Y_s(s)$ ,  $Y_d(s)$ ,  $X_1(s)$ ,  $X_2(s)$  and  $\Delta(s)$ . Synchronizing focus error  $\Delta(s)$  can then be calculated according to:

$$\begin{cases} X_1(s) = G_1(s)U(s), \\ X_2(s) = G_2(s)U(s), \\ Y_s(s) = KX_2(s) + Y_0(s), \\ Y_d(s) = K(X_2(s) - X_1(s)) + Y_0(s) \end{cases} \Rightarrow |\Delta(s)| = \left| \frac{Y_d(s) - Y_0(s)}{Y_s(s) - Y_0(s)} \right| |G_2(s)| |U(s)|, \quad (7)$$

where  $U(s)$  is known and  $G_2(s) \approx G(s)$  and  $G(s)$  could be obtained through calculation according to characteristic parameters [6].  $Y_s(s)$ ,  $Y_d(s)$ ,  $Y_0(s)$  could also be obtained from experiment, enabling the calculation of  $\Delta(s)$ .

### 3 Experimental results and analysis

The devices used in the synchronizing focus error detection system include a three-dimensional movable platform, optical pickup head SF-HD60S from SANYO Company, K9 biconvex lens GCL-010215, quadrant photodetector S4349 manufactured by HAMAMATSU, signal processing

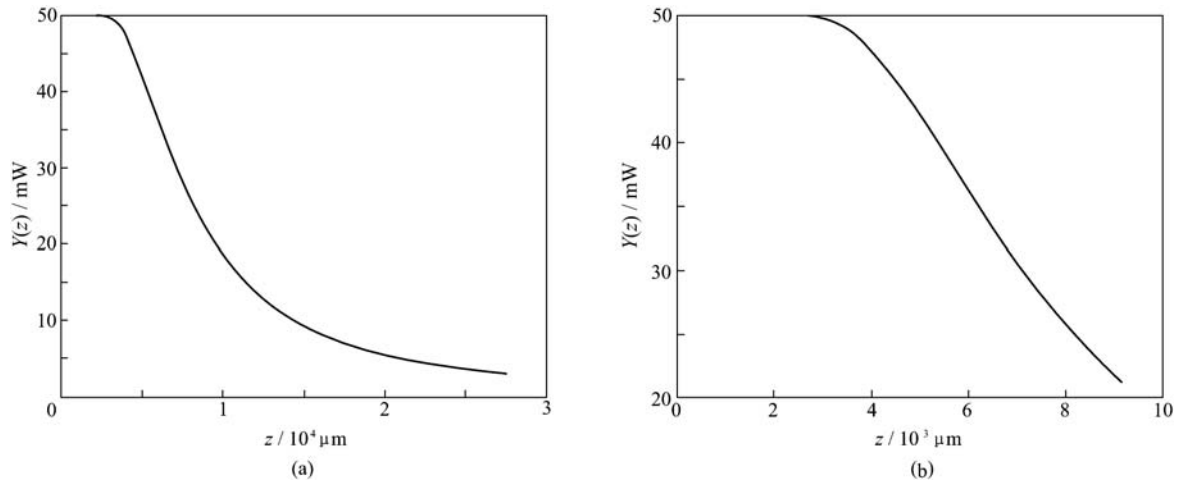


Fig. 3 Relationship of output energy and distance. (a) Integral detail; (b) partially enlarged detail

and control circuit, and 800 nm continuous laser. The parameters of all devices are as follows:  $f_1 = 3.07$  mm,  $N_A = 0.47$ ,  $a = f_1 N_A = 1.44$  mm,  $f_2 = 15.0$  mm,  $b = 4.5$  mm, and  $e = 3.0$  mm. According to Eqs. (5) and (6), to make the error detection system work in the linear area, the initial position parameters must be set as follows:  $d = 7.0$  mm,  $x = 9.0$  mm, and  $c = 7.0$  mm. The input driving signal is a sine signal,  $V_{pp} = 0.5$  V, the frequency is 0.8 Hz; at 1 to 10 Hz, the interval is 1 Hz; at 20 to 100 Hz, the interval is 10 Hz. To every frequency point, we recorded the output of the quadrant photodetector, the initial static state once, lower pickup movement state three times, and dual-pickup-head synchronizing movement state three times. During the whole experiment, the power of input laser was constant at 16 mW. Figure 4 shows the input driving signal of 20 Hz and the output of the quadrant photodetector under different states. It illustrates that both the driving signal  $U(t)$  and the output signal of photodetector  $Y_s(t)$  under a lower pickup head movement state are sine signals of the same frequency. It proves that the system works in a linear area and could detect the displacement of pickup head very well. Under a dual-pickup-head synchronizing movement state, the output signal of quadrant photodetector  $Y_d(t)$  mainly consists of the output of static state besides the synchronizing error signal  $Y_0(t)$ . According to Eq. (7), we analyzed the output signal in a frequency domain and calculated the synchronizing error amplitude  $|\Delta(s)|$  under a different frequency as shown in Fig. 5.

Because of the unstable power of a continuous light source and photodetector noise, the output signal  $Y_0(t)$

represents high randomness and amplitude and lower frequency vibration. Thus,  $Y_0(s)$  is the FFT transforming average of  $Y_0(t)$  under different frequencies in the calculation. The results indicate that the amplitude of synchronizing focus error is no more than  $13 \mu\text{m}$  when the frequency of input signal is no more than 40 Hz. The minimum amplitude is  $0.6795 \mu\text{m}$  under 20 Hz, and the second minimum amplitude is  $1.2556 \mu\text{m}$  near 9 Hz. From 60 to 80 Hz, the synchronizing focus error is more than  $100 \mu\text{m}$  because the nominal resonance vibration frequency of the voice coil motor is 66 Hz, and the system works near the resonance vibration frequency. By choosing the proper working frequency, the confocal dual-pickup-head synchronizing focus servo method can thus satisfy the need of a multi-layer data storage system.

## 4 Conclusion

In the development of a confocal dual-pickup-head multi-layer data storage system, validating the feasibility of the synchronizing focus servo method requires measuring the synchronizing focus error of the two pickup heads. In this paper, we put forward a new method to detect the displacement by using the linear relationship between the space length and output energy of the pickup heads. First, the linear condition of the detection system is calculated by using the ABCD transforming matrix method. Second, the amplitude of synchronizing focus error under different frequencies is calculated by using frequency-domain analysis. The experimental result shows that the synchronizing focus error is

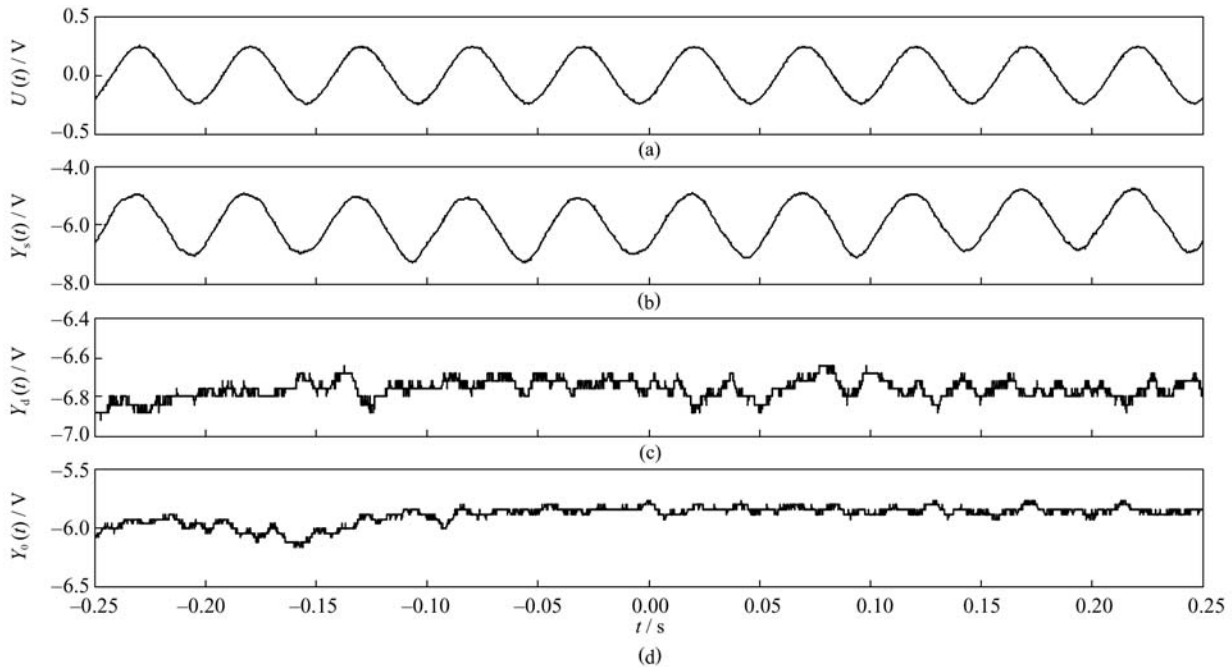
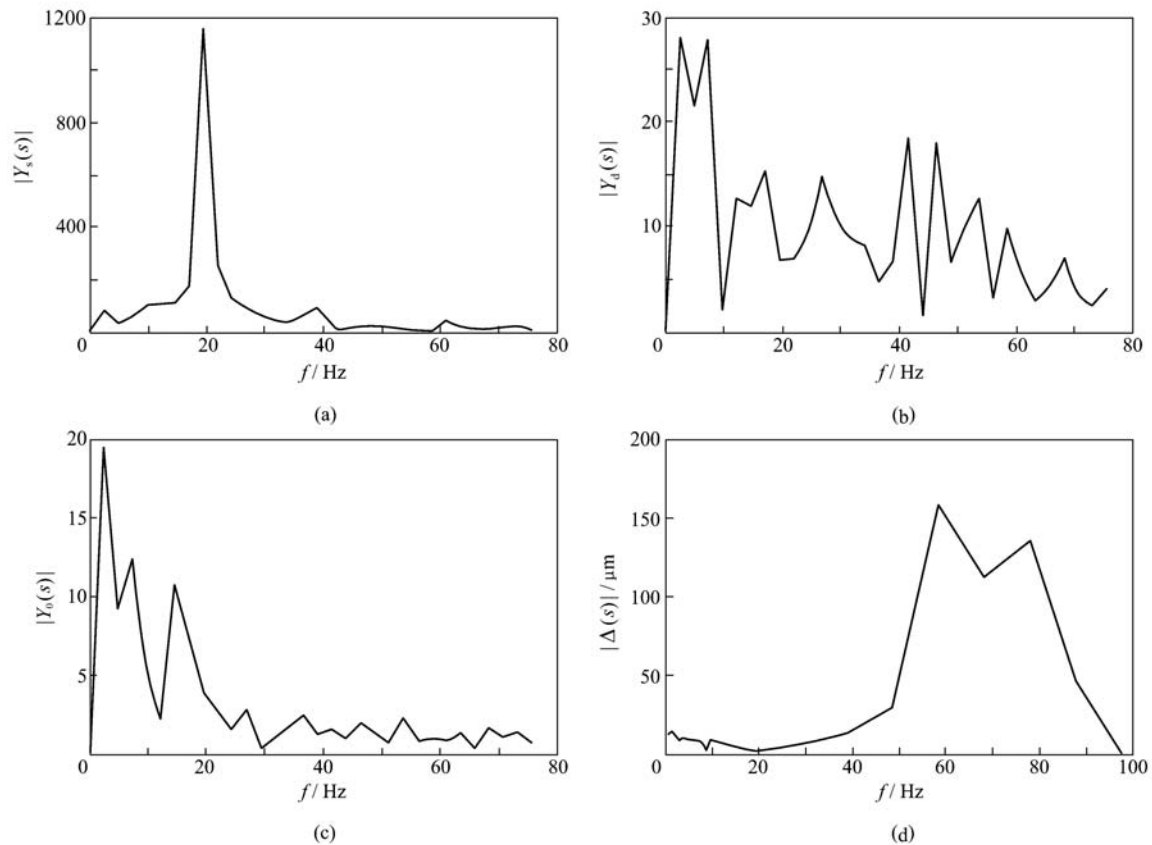


Fig. 4 20 Hz input signal and output signals of different movement states



**Fig. 5** Synchronizing error amplitude under different frequencies. (a) Output spectrum of lower pickup head movement; (b) output spectrum of dual-pickup-head synchronizing movement; (c) output spectrum of static state; (d) spectral amplitude of synchronizing focus error

relevant with frequency, and a minimum error frequency exists. Thus, when designing the system, we should make the frequency of the driving signal of voice coil motor close to the minimum error frequency to decrease the synchronizing focus error, improve the precision of synchronizing focus servo and make data reading and writing easier.

**Acknowledgements** The research project was supported by the National Natural Science Foundation of China (Grant No. 50335050).

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